The Instagram: A Novel Sounding Technique for Enhanced HF Propagation Advice

Rod I. Barnes,
G. Fred Earl
Riverside Research Organization
Rosslyn, VA, USA
rbarnes@rri-usa.org, fearl@rri-usa.org

Michael Papazoglou
STRAD Corporation
Arlington, VA, USA
map@stradcorp.com

Lee Burchett, Andrew J. Terzuoli, Jr.
Air Force Institute of Technology
Wright-Patterson AFB, Ohio, USA
lee.burchett.ctr@afit.edu, a.j.terzuoli@ieee.org

***Abstract*— Modern OTHR systems make extensive use of propagation support information for parameter setup advice. A novel method for increasing dimensionality and temporal resolution of this advice is demonstrated here using an instantaneously wideband waveform on a one-way path. A composite of pseudo-randomly phased, discretized, massively multi-channel signals is synthesized through a simple summing scheme. Upon reception the composite is rapidly processed in the frequency domain to produce channel scattering information simultaneously across the band. The channels may be collapsed in the Doppler domain to reduce to conventional oblique ionograms. Total integration time required to produce the full Doppler ionograms, even with low transmit powers, is reduced over conventional methods by up to three orders of magnitude leading to the term 'Instagram'. The technique is implemented on an oblique sounding system that provides the necessary direct digital arbitrary waveform generation and reception capability. A result from the initial field trial is provided.**

I. Introduction

Due to the dynamic nature of the ionosphere, OTHR systems require real time collection and analysis of data characterizing the RF environment at the receiver, and radio wave propagation to the areas of interest. Generally, the higher the resolution of this information, the better the performance obtained with the OTHR. Uses of these support data include frequency advice to the main OTHR [1,2,3], coordinate registration assistance [4,5], and spread clutter reduction.

Traditionally, OTHR advice systems that have produced range information have used chirped or pulsed signals, while systems that produce range and Doppler information use repetitive waveforms on a single channel [1]. These techniques provide reliable data within their sensitivities and resolutions. While the temporal resolution provided by these systems is adequate for many tasks, there has been a recent interest to characterize phenomena of a more rapid scale [6,7].

Here we seek to break traditional barriers in resolution by exploiting low power signals that are instantaneously wideband across the HF spectrum. This concept, while always theoretically possible, becomes more practically accessible with the advent of modern direct digital hardware capable of its production and reception.

Barnes and Earl [8] modeled a technique of summing discretized FMCW for the purposes of enhancing OTHR range resolution through wideband transmissions. By extending this idea to the entire HF band, ionograms can be contemplated that achieve high temporal and range resolution, and are capable of measuring Doppler shift information.

An immediate concern of an HF broadband technique is its impact on the RF environment. Several precautions are necessary before such a scheme is attempted, and an ultimate aim might be to have the technique as close to subliminal as possible. Ideas on how to approach this are detailed below.

II. Theory

The wideband waveform chosen is a sum of narrowband (e.g. 10 kHz) frequency modulated continuous wave (FMCW) signals that are distributed across the HF spectrum. The

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14. ABSTRACT

Modern OTHR systems make extensive use of propagation support information for parameter setup advice. A novel method for increasing dimensionality and temporal resolution of this advice is demonstrated here using an instantaneously wideband waveform on a one-way path. A composite of pseudo-randomly phased, discretized, massively multi-channel signals is synthesized through a simple summing scheme. Upon reception the composite is rapidly processed in the frequency domain to produce channel scattering information simultaneously across the band. The channels may be collapsed in the Doppler domain to reduce to conventional oblique ionograms. Total integration time required to produce the full Doppler ionograms, even with low transmit powers, is reduced over conventional methods by up to three orders of magnitude leading to the term ?Instagram?. The technique is implemented on an oblique sounding system that provides the necessary direct digital arbitrary waveform generation and reception capability. A result from the initial field trial is provided.

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starting phase of the waveform within each frequency channel is chosen to avoid large temporal impulses, and tapering is applied to limit interference into restricted portions of the HF spectrum. The bandwidth of the individual FMCW channels is a parameter that can be tailored to suit the environment. A relatively low bandwidth assists with agility in and around restricted or occupied channels but decreases range resolution when processing using standard FMCW pulse compression techniques. Higher resolution can be attained through the use of the phase ionosonde technique [9,10].

The expression for the waveform of an individual channel in the instagram is

$$x_k(t) = \exp(j2\pi f_k t) \sum_{m=0}^{M-1} a(t - mT) u(t - mT) \quad (1)$$

Where f_k is the frequency of the kth frequency channel, $u(t)$ is the linear FM chirp waveform

$$u(t) = \exp(j\pi(b/T)(t - T/2)^2) \quad (2)$$

where $a(t)$ is a tapering function to avoid interference into neighboring frequency channels, T is the waveform repetition interval (WRI), and b is bandwidth. The wideband instagram waveform is the summation over the individual narrowband FMCW signals and can be written as

$$x(t) = \sum_{m=0}^{M-1} a(t - mT) u(t - mT) \sum_{k=0}^{K-1} \exp(j(2\pi f_k t + \theta_k)) \quad (3)$$

where the phase terms θ_k are randomized to avoid large impulses in $x(t)$.

In propagation each signal will be subjected to individual effects including multi-mode, phase and group delay, frequency shift and spreading. Upon reception of the wideband signal, a bank of matched filters is applied to each waveform repetition interval in order to separate the narrowband channel data. The matched filter is designed to control the range sidelobes of each impulse response function $d(t)$. The frequency response of the matched filter (at baseband) is calculated as $H(f) = D(f)/U(f)$ for $-b/2 < f < b/2$ where $U(f)$ is the Fourier transform of the FM chirp waveform defined in equation (2). This matched filter is applied to each sweep m and each frequency channel f_k of the received waveform. In the frequency domain, the matched filter output for WRI m and frequency channel k is

$$Y_{k,m}(f) = H(f) X_m(f + f_k) \quad (3)$$

for $-b/2 < f < b/2$ where $X_m(f)$ is the Fourier transform of the m^{th} WRI of the received data.

Coherent processing across sweeps provides improved spectral resolution and signal gain and allows for the estimation of channel scattering functions (CSF) for each radiated channel across the band of transmission [1]. The Doppler dimension can be collapsed (integrated across) to provide a conventional oblique ionogram.

For every range-Doppler cell, in each CSF, phase progression with frequency can be used to increase range resolution using the phase ionosonde technique [9,10], and accounting for ionospheric dispersion. A method of interpolation across forbidden channels or channels with poor signal to noise is required if necessary within the required bandwidth. This methodology (without the interpolation), was described by Barnes and Earl [8].

III. MODELLING

The instagram waveform and processing can be modeled to demonstrate advantages using a wideband signal for ionospheric sounding. Figure 1(a) shows the time series produced by a composite of 10 kHz bandwidth FMCW channels using a 50 Hz waveform repetition frequency (WRF). The signal is digitized at 102.4 MHz for compatibility with the arbitrary waveform generator, upon which it would later be implemented. The frequency spectrum for this signal is shown in Figure 1(b), where it is clearly visible that power has been diminished in frequency bands that are forbidden under Federal Communications Commission (FCC) and military rules.

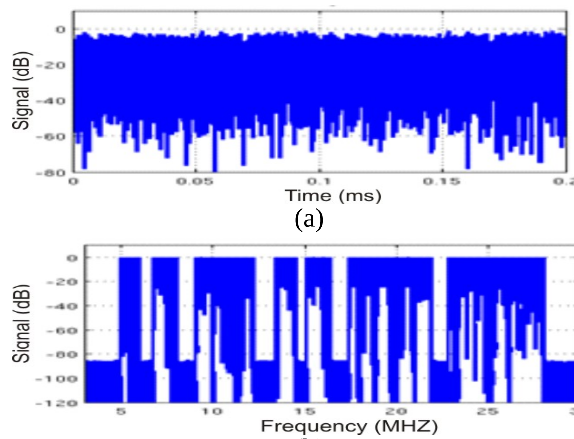

Figure 1. (a) Time and (b) frequency domains of an Instagram waveform

Guard bands around forbidden channels are also introduced. Tapering in the time domain for each WRI enhances the spectral containment of the FMCW signal around the edges of channels. Figure 2 shows the skirts of tapered (green) and non-tapered (blue) FMCW signals on the edges of restricted channels.

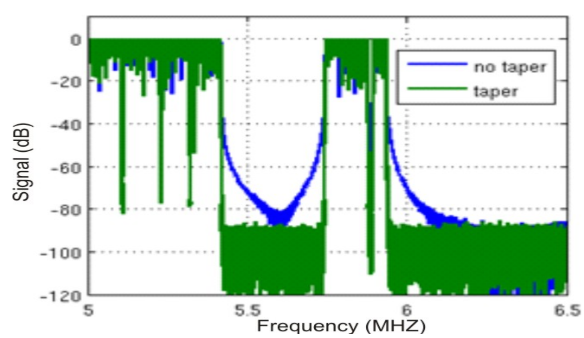

Figure 2. The effect of tapering on an instagram waveform near adjacent restricted channels

The time series data can be attenuated and delayed on the computer to simulate ionospheric effects. Processing as if received through the real receiver can be simulated. A slightly more realistic simulation can be accomplished in the lab with the actual hardware, by cabling the wideband receiver through attenuators into the arbitrary waveform generator. This situation is described in the next section.

IV. Implementation

Commercially available direct digital solutions for HF sounding have the ability to provide high dynamic range (16 bit), high speed (>>100 MHz) arbitrary waveform generation (AWG) across the HF band. The waveform nature will typically be constrained by onboard memory limits, but generation of the instagram waveform is routine. Computer generated time-series data at the necessary sampling rate may be created to a computer file and transferred to AWG memory for RF generation. A single sweep (all instagram channels have common WRF) is loaded, and the AWG handles repetition for the desired number of repeats or continuously until stopped by the user. For use as an HF sounder, the direct digital AWG can be coupled to RF conditioners to provide any required amplification.

In a realistic implementation using a 10 kHz bandwidth per FMCW channel implementation, about half the available channels across the HF band will be lost to restricted and heavily used bands. This still would amount to ~1500 individual channels in the composite waveform. This means that the power level in each channel for a 19 dBm low power amp output is reduced to about -12 dBm. Using a 10 W power amplifier would result in a -21 dBW/channel output.

Reception of the instagram waveform must be executed on an HF wideband capture system. For successful sounding reception, the capture system must have an RF front-end conditioning unit consisting of an HF broadband filter, ultra-linear amplifiers, and programmable attenuation. In a wideband capture system the high speed A/D output is directly recorded to a RAID rather than down converted as in normal radar or software radio operation. Processing of the instagram can then begin from a file.

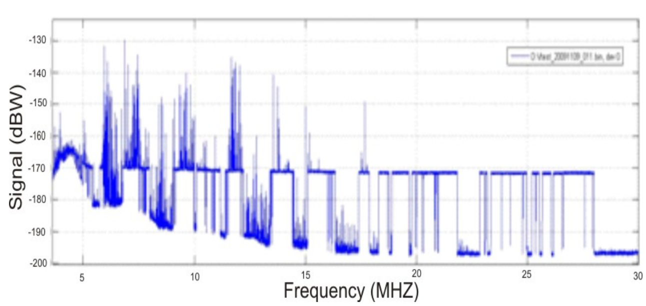

Figure 3 Power Spectral Density plot of the instagram waveform as received on a wideband capture system after 'propagation' with 90dB loss and environment connected.

By modeling the ionosphere using simple RF attenuators, a lab experiment using such equipment can readily be constructed. Moreover the real RF environment can be added in with the simulated instagram record through coupling the two signals. Figure 3 shows the recorded instagram after a 19 dBm transmission is subjected to 90 dB 'propagation' loss by insertion of RF attenuators. In practice attenuation will be greater on most frequencies resulting in a much less obvious detection. The relative amplitude was left large for illustration purposes, and to demonstrate the potential benefit of tailoring to the environmental and system gain levels.

It is immediately obvious that the instagram signal will be generally competing with higher background levels at lower frequencies than at higher frequencies. This suggests there may be value in providing more power to the lower frequency channels than the higher frequency channels in the band. This is achieved by simply applying a frequency-dependent weighting to different frequency channels of the instagram waveform. The weighted waveform along with a synthetic noise floor is shown in Figure 4. In this case the overall level of the instagram waveform on reception has been reduced to subliminal levels.

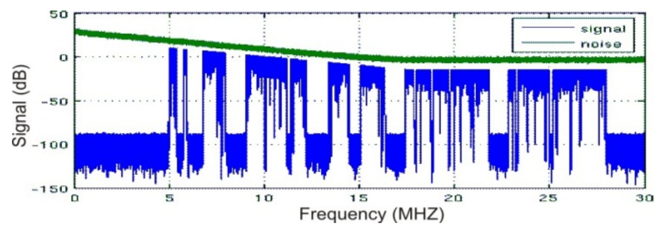

Figure 4 PSD plot of the weighted instagram waveform as received on a wideband system with simulated background noise level included.

Although the signal appears subliminal to other users it can still be extracted with matched filtering and coherent integration. This is depicted in Figure 5 with an illustrative simulation ionogram. No attempt has been made to insert delay and dispersion to the instagram waveform, which is why it appears at zero range at all frequencies.

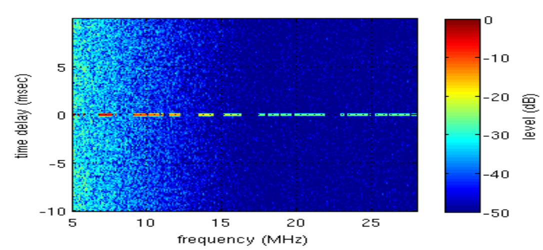

Figure 5 Modelled instagram against graded background noise denisty. No delay or dispersion was introduced into the simulation

V. Fielded Application Considerations and Sample Results

The instagram technique was tried on a 1610 km path from Florida to Ohio. Over this path the expected signal to noise ratio of each channel can be calculated using the transponder form of the radar equation viz.

$$SNR(dB) = P_t + G_t + G_r + 20log_{10}\lambda - \varepsilon - N - A - 20 * log_{10}(4\pi r).$$

In our experimental setup, for a 10 second coherent integration time, some representative numbers for propagation losses on a 1610 km path during the day at 10 MHz are:

$$P_t = Transmitter\ power\ per\ channel = -21\ dBW$$

$$G_t = Transmit\ Antenna\ Gain = 2\ dB$$

$$G_r = Receive\ Antenna\ Gain = 2\ dB$$

$$\lambda = radio\ center\ wavelength = 20\ m$$

$$\varepsilon = Antenna\ and\ Cable\ Efficiency\ Losses = 10\ dB$$

$$N = Noise\ Power\ in\ Spectral\ Estimate\ = -170\ dBW$$

$$A = Ionospheric\ absorption\ loss\ = \sim 10\ dB$$

$$P_l = \ 20 * log_{10}(4\pi r) = propagation\ loss = 146\ dB$$

providing an expected SNR of 17 dB. While this may seem marginal, one of the aims of the system is to ensure that the transmissions are near-subliminal for other users of the spectrum. Receivers that are even a modest distance from the transmitter utilizing a 3 kHz bandwidth and demodulation unrelated to the FMCW waveform should not be significantly disturbed by the presence of the instagram with broadband power in the vicinity of 10 W. An obvious corollary is that the instagram will not be detected by its own receiver in channels occupied by large signals, but this is in keeping with its general concept of operation. In an OTHR context, reception with an antenna array could easily provide another 25 dB improvement in signal to noise. A more advanced arrangement would also split transmit energy into fewer channels avoiding areas of heavy use (such as broadcast and amateur bands) and above the MUF transmissions. It is envisioned that another 4-5 dB in SNR could thus be captured. Coherent integration above 10 seconds could be used to increase signal to noise up to a point, before incoherence introduced by the ionosphere renders further integration useless. It is imagined that 3 dB might be captured this way if necessary. Increased power per channel could be considered as a last resort, and would occur at the risk of interfering with other users of the HF spectrum.

A live example of capture and processing of an instagram is shown in Figure 6, along with the CSF slice at 14 MHz. This particular example was limited to transmission over a finite frequency range due to frequency restrictions on test, and as a means of investigation into SNR levels as a function of the number of channels. The component FMCW waveforms were 20 kHz bandwidth and 20 Hz WRF. No attempt at higher resolution range processing has been attempted.

Collection of Doppler data across the HF band with this resolution by conventional sounding would take an hour or more, while here it is has taken just a few seconds. This represents an increase in achievable temporal resolution of three orders of magnitude.

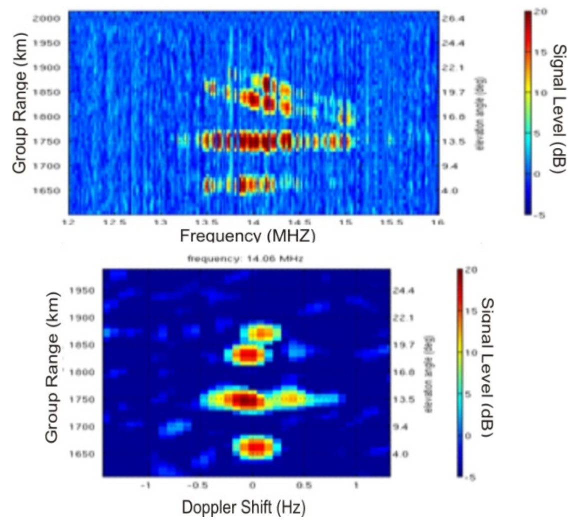

Figure 6 Real instagram fragment captured on a 1610 km ground path (top panel) along with a CSF from the same data at 14 MHz.

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